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The primary tasks associated with this contract were characterization and calibration of an RCA 8852 photomultiplier tube and a Varo image intensifier. The photomultiplier was characterized by its spectral response, absolute sensitivity, quantum efficiency, scan uniformity, dark current vs temperature, pulse-height distribution, and noise figure. The Varo intensifier was characterized by its response as a function of bias voltage both in the dark and while irradiated by an LED light source. This final report discusses the tests we performed and compares them with data in the open literature and with data obtained by means of private communication from other researchers in the field. Some tests are also discussed in the bimonthly report covering the period from June 26, 1986 to August 25, 1986.

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Introduction. We have carried out an investigation into the cause of why most phosphor screens fail to release a detectable burst of light in nearly half of the occasions where they are struck by a single photoelectron (reference 1). The present work differs from all of our earlier work, where previously we have directly measured the single electron counting efficiency in operating image intensifiers (reference 2). In this new study we have examined the very fine-scale cathodoluminescent properties of individual grains of P-20 phosphor powder using a scanning electron microscope (SEM). This technique allows observation for the very first time of the cathodoluminescent response of an area within a single phosphor grain that is at least one hundred times finer than an area resolvable by purely optical techniques. We have consequently been able to test many hypotheses concerning the cause of the disappointingly low counting efficiency of phosphor screens used in diode type image intensifiers.

Method. The electron microscope was instrumented so that three distinctly different types of images could be studied: 1) A standard "secondary electron" mode (SE), where images of the speciman are formed via collecting the secondary electrons emitted by the point being struck by a scanning electron beam; 2) A "cathodoluminescent" mode (CL_{FO}), where light emitted while one point is being struck by the electron beam is collected by a fiberoptic butted up against the output faceplate of the screen, and the resultant brightness of the image displayed on a CRT at that point is proportional to the amount of light emitted from the speciman; and 3) A second "cathodoluminescent" mode (CL_{EL}), identical to the CL_{FO} mode, only the light collected is that which is emitted toward the electron beam side of the screen, rather than that emitted through the output faceplate of the screen. The image displayed on the CRT of the SEM may be recorded on polaroid film. A second CRT displays the video waveform of the raster line currently being written on the first CRT. We have made video tapes using a standard video camera of both CRTs simultaneously. Slow-motion playback of the tapes later allow us to obtain photometric measurements of images shown on the first CRT through analysis of the waveform displayed on the second CRT. The figures accompanying this report are xerox copies of polaroid prints taken with the electron microscope. They are labeled according to which mode was used, namely SE, CL_{FO}, or CL_{EL}. In these pictures the black and shiny aluminum layer has been peeled away from the phosphor layer in order to see the grains.

Samples tested. SEM data have been recorded for many samples of P-20 phosphor screens that have been manufactured by Proxitronic using various modifications to their processing steps in an attempt to understand and improve the counting efficiency. The sample screens are described as follows:

1) all normal steps carried out,
2) settled phosphor only, no further steps,
3) settled phosphor, aluminized, lacquer baked out,
4) screen from previously operating tube, coarse grained, measured C.E. of operating tube = 42%,

5) screen from previously operating tube, 2x thickness, no electron scrubbing, measured C.E. of operating tube = 50%.
6) screen from previously operating tube, 4x thickness, measured C.E. of operating tube = 70%.

Following a preliminary SEM analysis of the above screens, Proxitronic then prepared a second set of samples as follows:

1) settled phosphor, 1.5x thickness, standard lacquer thickness, standard aluminum layer, 420°C lacquer burnout, nothing more (i.e., no black layer, no electron scrub, no other bake).
2) like (1), only without lacquer burnout step.
3) like (1), only with twice lacquer thickness.
4) like (1), only with half lacquer thickness.
5) like (1), only with double thickness of aluminum.
6) like (1), only with black layer and with half of screen electron scrubbed and other half not.

Results from preliminary SEM analysis.

1) In the standard thickness screens (0.7 mg/cm^2), the SEM images taken in the two cathodoluminescent modes (CL_{EL} and CL_{PO}) show that voids, or holes, in the screens constitute roughly 10% of the total projected area of a screen. This directly accounts for a 10% loss in counting efficiency for such screens. In earlier optical microscope examinations of screens, we were unable to accurately determine the size of these holes, but suspected they could be large enough to explain the nearly 50% loss in counting efficiency that is typical of screens. The electron microscope images conclusively refute this large of an effect. The electron microscope also clearly shows that 2x and 4x phosphor thickness screens are too thick, and that a 1.5x thickness is optimum for reducing the area of holes to a negligible level (i.e., less than 1% of the screen surface). Making screens thicker than 1.5x creates the undesirable effect of reduced gain via absorption of light by underlying grains. This is dramatically revealed in CL_{PO} pictures of the 1x, 1.5x, 2x and 4x screens.

2) The cathodoluminescent images have revealed that there exist a few grains that are virtually dead and that other grains are of very reduced efficiency. This is in marked contrast to our findings using the industry-accepted technique of examining screens by shining UV light on them and by inspecting the luminescing grains with an optical microscope. Using this optical method we have never detected even one dead grain. Nonetheless, the number of totally dead grains revealed by the SEM is in fact quite negligible (less than 1%).

3) Some intensifier manufacturers have cautioned against the use of the very tiniest grains, reportedly observing that such grains are dead. In all our SEM tests, there is no evidence that the smallest grains (0.5 micron diameter) have a different cathodoluminescent efficiency than the largest grains (4 microns diameter).

4) At least 80% of all grains of a screen that may be directly viewed by the electron microscope may be classed as having a "typical cathodoluminescent structure". The typical grains are described as follows:

a) They appear to cathodoluminesce over 100% of their surface exposed to electrons, shown in both CL_{FO} and CL_{EL} modes.

b) They appear uniformly sensitive (to better than $\pm 10\%$) over their entire surface, and contain no apparent super-sensitive, or insensitive, spots or shells or cores shown in both CL_{FO} and CL_{EL} modes.

c) The peak-to-peak variation in response from one of these "typical" grains to another "typical" grain <u>on the same screen</u> is less than $\pm 15\%$.

5) Besides these typical grains, every screen contains a small percentage of grains (1-10%) that are dead, or have small dead areas, or have small high-sensitivity areas, etc. Although interesting, these grains appear to have very little effect on the overall performance characteristics of a screen.

6) In the early phases of our study, it appeared as though most of the grains in the top layer (i.e., the grains nearest the aluminum) were of reduced cathodoluminescent efficiency, even in the CL_{EL} images. However, further analysis reveals this is a false impression and is simply due to an optical effect between the top grains and the CL_{EL} sensor. Note: In the CL_{FO} mode, the top grains are always darker because their light is absorbed by lower grains situated between them and the CL_{FO} sensor.

7) Another property discovered in the early phases of our study is that grains that are excavated from the screen surface are roughly 50% brighter than the remaining undisturbed grains, when observed in the CL_{EL} mode. This property, along with the earlier suspected low-efficiency of top grains mentioned in item (6) above, led us to suspect that the excavated grains were predominantly from the bottom layer of screen and that this bottom layer had been protected from a manufacturing process that had selectively reduced the sensitivity of the top layer grains, but not the bottom grains.

<u>Results from second set of screen samples.</u> The second set of samples manufactured by Proxitronic (see list given in section, "Samples tested") were prepared in order to allow us to test specific processing steps suspected of destroying the top layer of grains more than the bottom layer. Any step that selectively destroys the top grains would normally go undetected in screen quality-control test procedures performed during normal manufacture because the top layer is hidden from view via the aluminum layer of the screen. Recognizing this, we were very encouraged by our initial SEM results that the second test samples could identify the cause of low counting efficiency. In the summary of results that follows, we discover that the earlier interpretation of screens containing a partially destroyed top layer of grains is wrong and, indeed, that no screen

manufacturing process thus far examined appears to damage the grains.

1) In our preliminary SEM analysis we had found what appeared to be a general progression in the number of damaged grains with each successive screen processing step. However, results from the additional samples and repeated and improved tests of the earlier samples have revealed that the earlier suspicians are unfounded, and that the proper explanation lies in certain optical effects of the CL_{EL} sensor, as already mentioned in items (6) and (7) of the section "Results from preliminary SEM analysis." The important new results follow.

2) The ratio of CL_{EL} signal from the average gray level of a screen to the signal from the very few brightest grains is found to be virtually a constant for all screens examined, and is 0.68 $\pm$0.02. This includes screens ranging from a settled-phosphor-only through a 4x-thickness-screen removed from a previously operating tube. Thus, no processing step was found to influence this ratio. (Earlier, we had thought a steady progression in this ratio existed, but now we realize such evidence was incorrectly influenced by extraneous optical effects of particular samples.)

3) The number of dead and partially destroyed grains in both the top and bottom layers of a screen seems to be rather similar among all samples of screens examined, <u>including</u> even the sample without lacquer burnout and the settled phosphor only sample. (Again, earlier we had been misled in this conclusion by various optical effects and by the effects of variable electron voltages applied in some of the early tests.)

4) In repeated attempts, we finally were successful in scraping away with a razor blade only the top layer of grains from a screen. In the resulting exposed bottom layer of grains, there was no detectable difference in the CL_{EL} signal strength from these grains or the surrounding undisturbed top-layer grains.

5) By studying CL_{EL} images of many different screen samples where grains had been purposely excavated from the screen layer, we discovered that the reason such grains appeared 50% brighter than all others was due to an optical effect with the CL_{EL} sensor, and not to an inherent high efficiency of the excavated grains. This discovery was ultimately responsible for our determining that the dark-core/bright-halo appearance of the topmost grains was also due to an optical effect. Earlier, we had misinterpreted this appearance as due to partial damage of top grains.

6) In the sample where half of the screen was electron scrubbed and the other half was not, there was absolutely no detectable difference in the cathodoluminescent efficiency or structure between the two halves.

Conclusions and recommendations. The most clearcut result of this SEM investigation is that phosphor screens manufacatured by Proxitronic are slightly too thin for optimum counting efficiency (and we suspect this is likely to be true for screens manufactured by others as well). There is no SEM evidence that grain size, within the size range of the Riedel de Haen powder examined here, influences the counting efficiency of a screen. (However, we should note that there is a modest suggestion in our counting efficiency measurements in operating intensifiers that, if indeed there is a measurable difference, small grains may perform better than larger ones.) A finite number of dead or reduced-sensitivity grains are present in all screens, but the percentage is negligible. Finally, there is no evidence that any of the screen processing steps carried out at Proxitronic damage or otherwise alter the cathodoluminescent properties of the original phosphor powder.

Therefore, although we undertook this SEM project with considerable enthusiasm that we would be able to identify one or more phosphor screen processing steps that were damaging the cathodoluminescence of the original phosphor powder, it now seems clear that none of the earlier plausible candidates are at fault. Having eliminated a number of likely explanations, of course, means that we simply must search elsewhere for the true cause. At this moment, the most likely explanation would seem to be that there exist one or more steps employed by the manufacturer of the phosphor powder proper (e.g. at Riedel de Haen) that is at fault. We earlier had dismissed this possibility on the basis that nearly all intensifiers we have analysed, from a variety of tube and phosphor manufacturers, have a similar, low counting efficiency. Moreover, the one intensifier manufacturer that has produced phosphors of high counting efficiency at least some of the time (although not all of the time), is Varo, and Varo claims to have used the same supplier of phosphor as the present Proxitronic powder, Riedel de Haen.

Toward learning what creates a high counting efficiency phosphor, we plan to carry out the following steps in the future:

1) Examine with the SEM a phosphor screen that has been dismantled from a previously operating intensifier that we have measured to have a high counting efficiency (selected from various reject Varo tubes we presently have). To date, we have examined with the SEM only one Varo screen, and it was from a tube of unknown counting efficiency.

2) Measure the counting efficiency of a Proxitronic intensifier having a brushed-on P-20 phosphor screen, instead of their standard settled phosphor screen.

3) Measure the counting efficiency of ITT intensifiers having P-47 fast-response phosphors.

4) Measure the counting efficiency of Proxitronic intensifiers having X-3 fast-response phosphors.

5) Discuss our results with producers of raw phosphor powder and collaborate with same in producing a high counting efficiency phosphor.

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1) The Lost Photon Problem in Image Intensifiers (R.H. Cromwell) 1984, Bulletin American Astronomical Society, 16, No. 4, 904 (Abstract). Steward Observatory Preprint No. 565 (Full Paper).

2) Toward Solving the Lost Photon Problem in Image Intensifiers (R.H. Cromwell) 1986, Instrumentation in Astronomy VI, David L. Crawford, Editor, Proceedings of the SPIE, 627, 610.

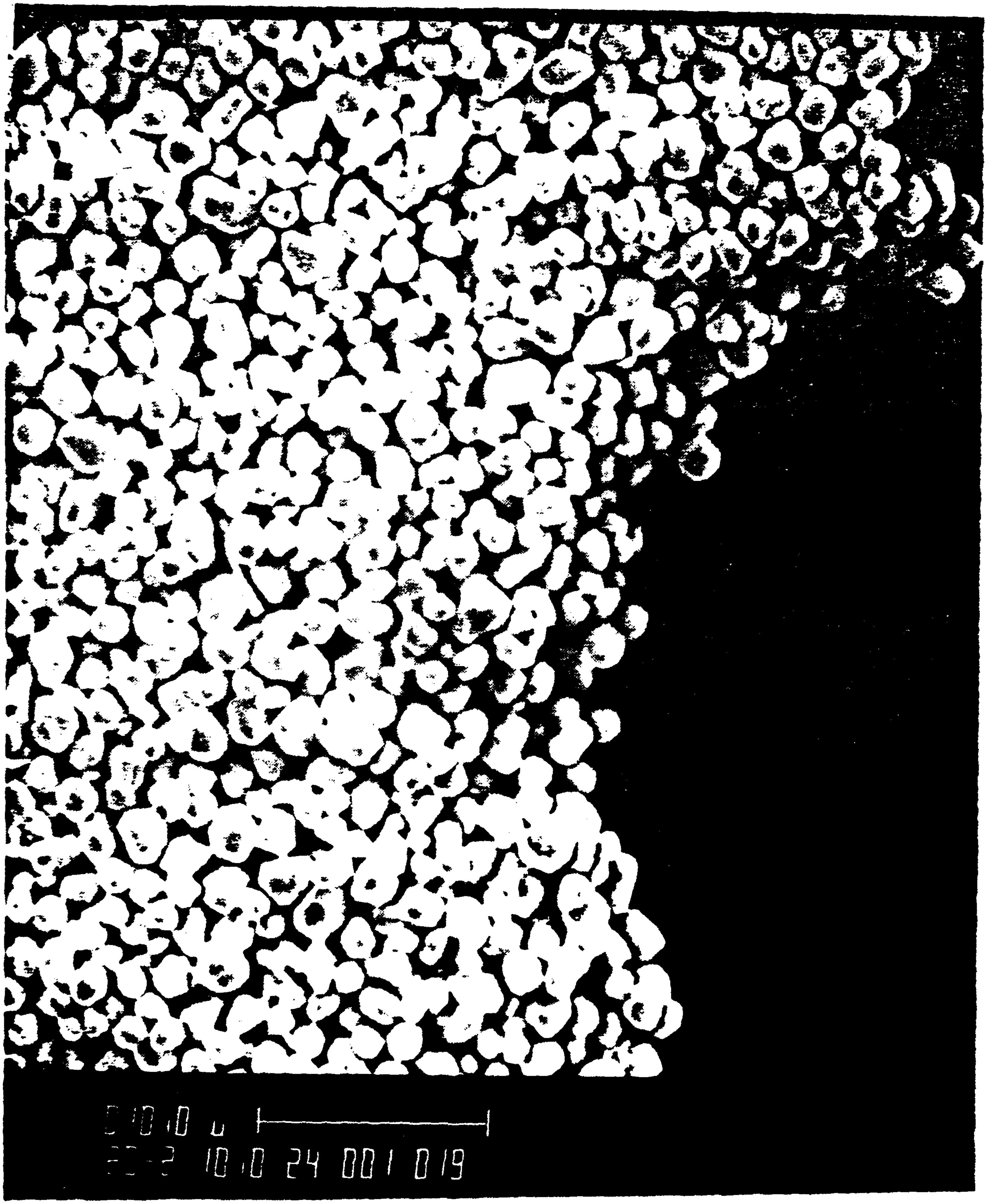

Figure 1. SE image of 2x thickness screen from a previously operating intensifier.

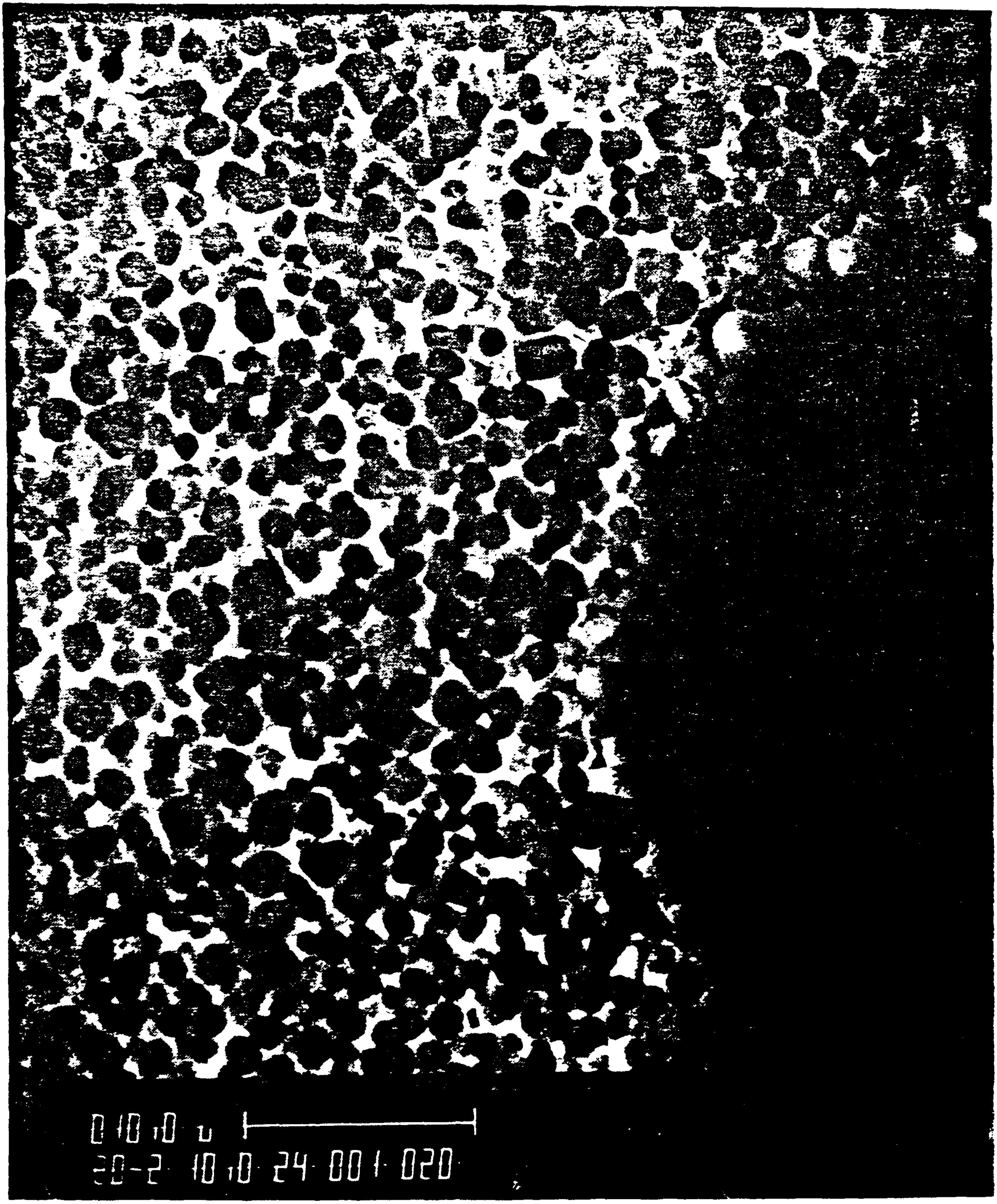

Figure 2. CL image of same region as shown in Figures 1 and 3.

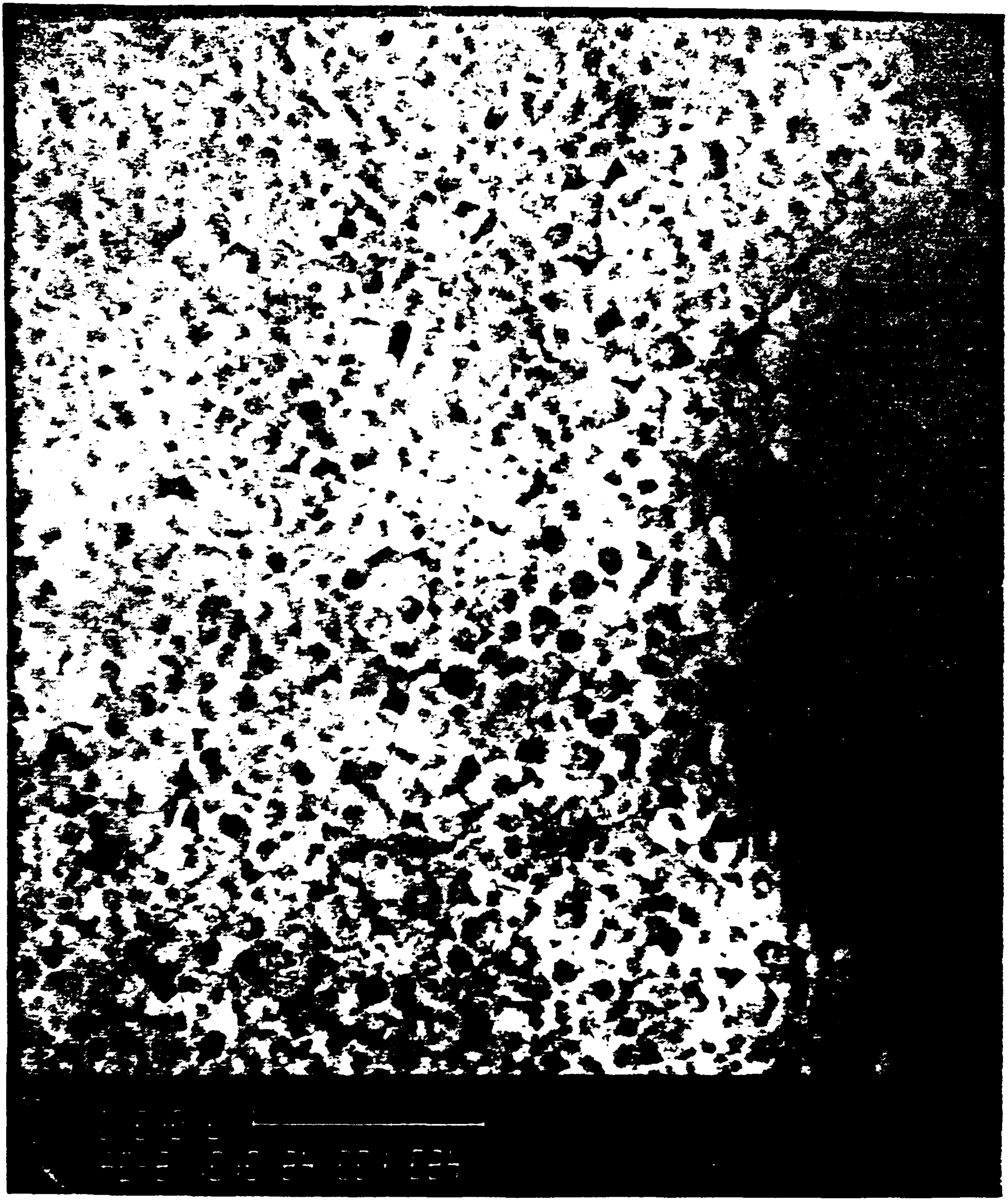

Figure 3. CL_{el} image of same region as shown in Figures 1 and 2. There are very few dead grains and virtually no voids in this 2x thick screen. The appearance that some of the top-most grains cathodoluminesce with a somewhat dark core and bright halo is due to optical effects of the CL_{el} sensor, and is not a true character of the phosphor powder.

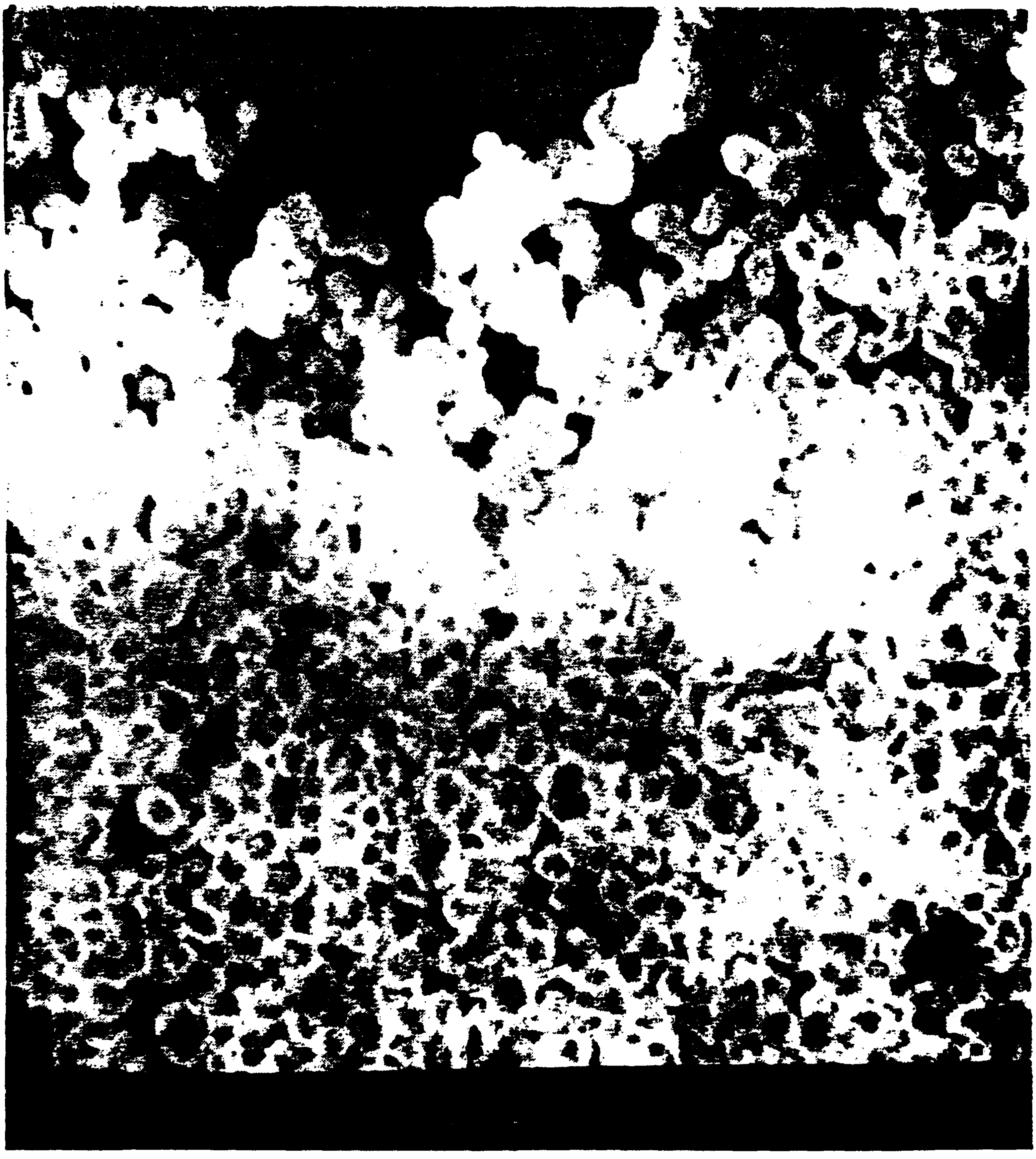

Figure 4. CL_{el} image of 1.5x thickness screen prepared without the lacquer burnout step that normally follows the aluminizing process. The grains of this screen are found to have virtually identical cathodoluminescent properties to the grains of fully processed screens that have been dismantled from previously operating intensifiers. The exceptionally bright clumps of grains in this photograph are grains that have been excavated from the screen. Their extra brightness arises from optical effects of the CL_{el} sensor, and is not an inherent property of the grains.

Figure 5. CL image of screen that has had half of its surface electron scrubbed (that half above the three scratch marks devoid of phosphor) and the other half not electron scrubbed. There is no detectable difference in the cathodoluminescent properties between the two halves.

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